Shear Stress and Sediment Resuspension in Canopy- and Meadow-Forming Submersed Macrophyte Communities

by William F. James, John W. Barko, and Malcolm G. Butler

PURPOSE: This technical note examines the impact of differing biomass levels and plant architectural types on bottom shear stress and sediment resuspension in shallow systems. Studies were conducted at Lake Christina, Minnesota, in late August-early September 1998, when macrophyte biomass levels exceeded 200 g/m^2 and in June 2000, when biomass was greatly reduced (< 20 g/m^2). The macrophyte beds that were studied were dominated by either a canopy-forming species (*Myriophyllum sibiricum*) or a meadow-forming species (*Chara canescens*). Information obtained from this study may be used to modify resuspension models to account for the impacts of macrophyte communities on bottom shear stress and sediment resuspension in shallow systems.

INTRODUCTION: The water quality of shallow aquatic systems is often dominated by wind-generated sediment resuspension in the absence of submersed aquatic macrophytes, leading to high turbidity, low light penetration, and excessive algal growth. Macrophytes can play an important role in improving the water quality of these systems by stabilizing the sediment from wave activity and resuspension (James and Barko 1990, 1994; Dieter 1990; Barko and James 1998). Wave energy that would otherwise impart a shear stress at the sediment interface in excess of the critical shear stress is dissipated by dense macrophyte coverage. Thus, one goal of shallow lake rehabilitation is the promotion and maintenance of stable submersed macrophyte communities for purposes of reducing sediment resuspension, sediment export, and improving water quality (Hosper 1989; Hosper and Jagtman 1990; Hanson and Butler 1990; Jeppesen et al. 1997).

A variety of factors (e.g., lake level fluctuations, increased densities of benthic fish communities, strong storms or high winds, anthropogenic removal of plants) may lead to a deterioration from the macrophyte-dominated state to a turbid, algal-dominated state (Maceina and Soballe 1990; Scheffer 1990; Scheffer et al. 1993; Breukers, Van Dam, and de Jong 1997). Reestablishment of macrophyte communities to encourage water quality rehabilitation in shallow systems presents some choices to the lake manager. Certain desired plant species or communities can be selected and propagated in sheltered areas, behind constructed islands, or in protective cylinders as starter colonies to serve as propagule sources for expansion throughout the system (Smart and Dick 1999). However, information is needed on the effectiveness of canopy-forming (i.e., biomass structure near the lake surface) versus meadow-forming species (i.e., low growth forms) of macrophytes in impacting shear stress and reducing sediment resuspension. A better understanding of the role submersed plant architecture and biomass level play in sediment resuspension dynamics will assist in management decisions regarding what types of plant species to propagate or to discourage from growth in shallow systems. In this study, we examined the impacts of macrophyte communities dominated by a canopy-forming (*Myriophyllum sibiricum*) and a meadow-forming (*Chara canescens*) species on bottom shear stress and sediment resuspension in Lake Christina, Minnesota.

STUDY SITE: Lake Christina is a large (1,620 ha), shallow (mean depth = 1.25 m) glacial lake located in western Minnesota. Since 1990, the lake has supported an extensive community of

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submersed macrophytes dominated by *Potamogeton pectinatus* and the macroalga *Chara canescens*. *Myriophyllum sibiricum* is also abundant and occurs in nearly monospecific stands, particularly in the northern region of the lake. The lake underwent a biomanipulation consisting of rough fish eradication and restocking with largemouth bass and walleye in 1987 in an effort to reduce bioturbation, increase zooplankton grazing pressure on algae, and stimulate submersed macrophyte growth (Hanson and Butler 1990, 1994).

METHODS: Studies on shear stress and sediment resuspension were conducted in Lake Christina during the summers of 1998 and 2000. Two stations were established; one in a nearly monospecific stand of *Chara* and one in an adjacent stand of *M. sibiricum* in the north-central area of the lake for continuous monitoring of in situ turbidity (Figure 1). This area of the lake was chosen because water column depths within each macrophyte bed were similar (1.2 to 1.4 m deep). The distance between the two stations was approximately 100 m.
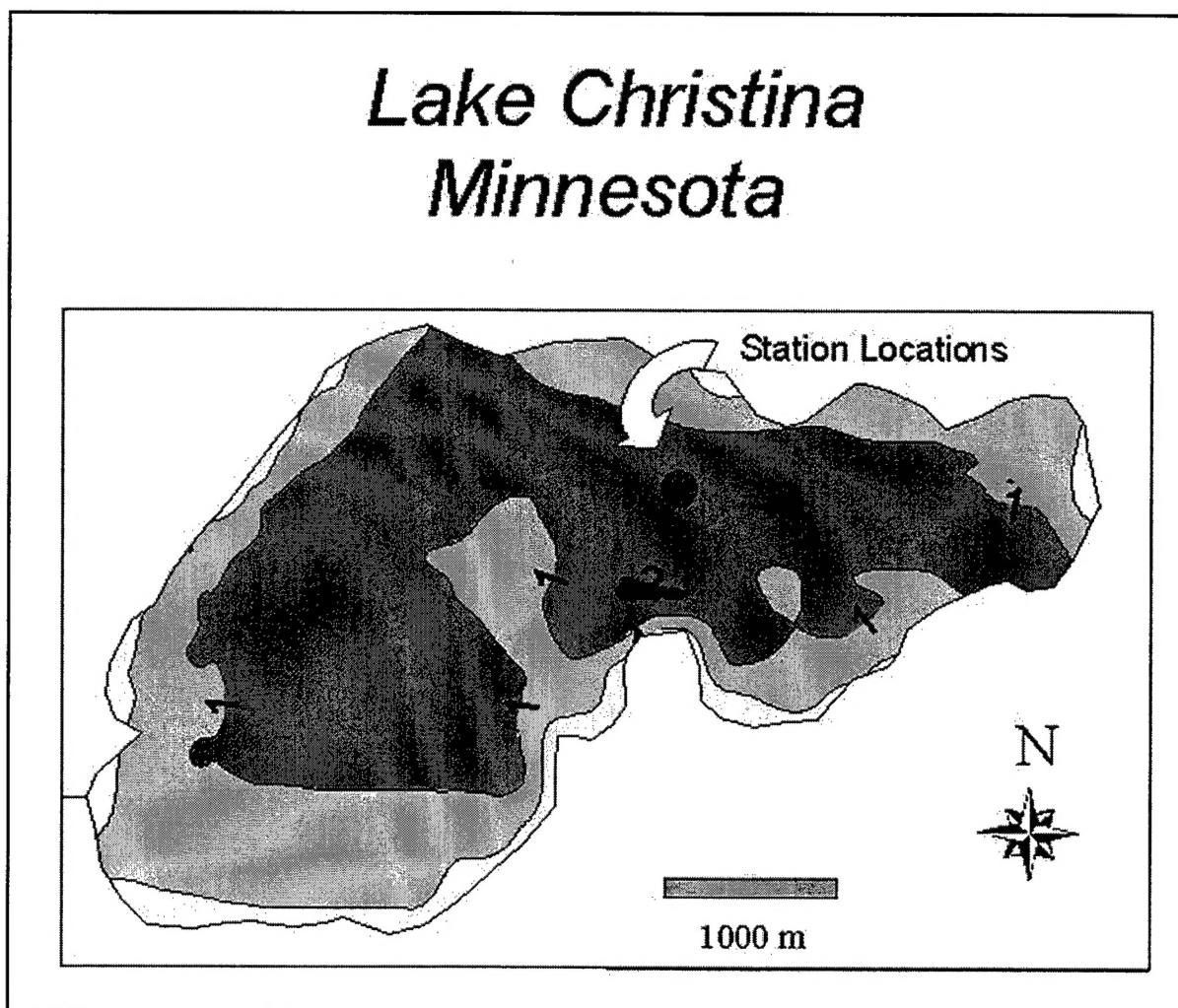

Figure 1.   Bathymetric map of Lake Christina showing the location (solid circle) of the adjacent *Chara* and *Myriophyllum sibiricum* beds. Depth contours are in 0.5-m increments. The southeast basin of Lake Christina is not shown

Turbidity was measured 0.25 m above the sediment surface at 15-min intervals at each station using YSI 6000 data sondes equipped with turbidity probes (Model 6026, YSI Incorporated, Yellow Springs, Ohio). The probes were pre- and post-calibrated with standard solutions (range of 0 to 100 NTU) purchased from YSI (YSI 6073, YSI Incorporated, Yellow Springs, OH). At approximately biweekly intervals, the data sondes were serviced, cleaned, recalibrated, and redeployed.

Wind speed and direction were measured at 15-min intervals at a weather station (Wescor, Inc. Model 824) deployed on a stand in the lake near the two sampling stations. The wind anemometer was located ~ 2 m above the lake surface. The wave models developed by Carper and Bachmann (1986), Hamilton and Mitchell (1996), and Bailey and Hamilton (1997) were used to determine effective fetches and theoretical (calculated) bottom shear stresses (dynes cm^{-2}) at the sediment interface at the *Chara* and *M. sibiricum* stations using continuous records of wind speed and direction. The theoretical bottom shear stress was calculated as:

$$\tau = H\left\{\frac{\rho\left[\upsilon\left(2\pi/T\right)^3\right]^{0.5}}{2\sinh\left(2kh\right)}\right\}$$

where τ is the calculated bottom shear stress, H is the wave height (cm), ρ is the density of water (1 g cm^{-3}), T is the wave period (s), v is the kinematic viscosity, k is the wave number ($2\pi/L$ where $L =$ wave length, cm), and h is the water depth (cm). Since the calculation does not include the impacts of submersed macrophytes on wave activity, calculated bottom τ is interpreted as a theoretical reference shear stress only.

The critical bottom shear stress (τ_c) of sediments in Lake Christina was determined experimentally using a particle entrainment simulator (PES) designed exactly as described by Tsai and Lick (1986). The PES consisted of a vertically oscillating, perforated acrylic grid that was driven by a computer-controlled motor. The grid was positioned so that the bottom of its oscillation cycle occurred exactly 5.08 cm (2 in.) above the interface of an intact sediment core. A cam on the motor shaft allowed the grid to oscillate up and down for a distance of 2.54 cm (1 in.).

In July 1998, five intact sediment cores, 10 cm in depth, were collected in the vicinity of the *Chara* and *M. sibiricum* stations using a 15- by 15-cm box corer (Wildco Wildlife Supply Co.) for determination of τ_c. The sediment contained in the box corer was transferred to a 13-cm (5-in.) diameter by 20-cm acrylic cylinder by carefully slipping the cylinder over the sediment enclosed by the box core sleeve and sliding a thin plexiglass disk underneath the cylinder to contain the sediment. Cores were transferred to the laboratory with water overlying the sediment to minimize changes in physical characteristics (moisture content and density) that would have occurred due to desiccation. In the laboratory, 1.36 L (to a height of 5 in.) of filtered lake water was carefully siphoned onto the sediment surface of the sediment core system before inserting it into the PES.

To determine τ_c, the motor of the PES was programmed to oscillate above the sediment interface in a stepwise manner from 0 to 800 revolutions per minute (rpm) at 100-rpm increments over 10-min

intervals. At 8 min into each rpm cycle, a 50-mL sample was collected 2.54 cm below the water surface using a peristaltic pump. Water removed as a result of sampling was simultaneously replaced with filtered lake water using a peristaltic pump. Samples were analyzed for total suspended sediment (TSS) according to the American Public Health Association (APHA) (1992). Measurements in rpm's were converted to τ using the calibration curve developed by Tsai and Lick (1986; Figure 5, page 317) for levels ranging between 430 and 750 rpm. Linear interpolation was used to estimate τ for levels that occurred below 450 rpm and above 750 rpm. Thus, τ ranged from 0 to nearly 6 dynes cm^{-2}. The τ_c was estimated as the inflection point where TSS increased in an exponential pattern. In the absence of submersed macrophyte communities in Lake Christina, sediment resuspension was predicted to occur when calculated bottom τ exceeded τ_c.

Additional replicate (10 cores) sediment cores were collected using a Wildco KB sediment corer (Wildco Wildlife Supply Co.) equipped with an acrylic core liner (6.5 cm ID and 50 cm length) for determination of sediment characteristics. The upper 10 cm of sediment was dried at 105 °C to a constant weight for determination of moisture content and sediment density (Håkanson 1977). An additional portion of the sediment sample was combusted at 500 °C for determination of percent organic matter (Håkanson 1977).

The rate of dissolution of gypsum spheres was measured near the lake surface (i.e., 0.15-m depth), at mid-depth (0.5-0.6 m), and near the bottom (0.10 m above the sediment surface) at each station to determine the effects of a canopy-forming versus a meadow-forming macrophyte community on wind-generated turbulence throughout the vertical water column and τ near the sediment interface. The spheres, measuring 4.5 cm in diameter, were constructed using a modification of the procedures described by Petticrew and Kalff (1991). A 60:40 mixture of gypsum (as $CaSO_4 \cdot 2H_2O$) and water, respectively, was poured into a rubber mold containing an anchoring bolt and allowed to set up for at least 30 min. The spheres were removed from the mold, dried at 39-40 °C for a minimum of 48 hr, and weighed for determination of dry mass. Pre-weighed spheres were deployed in the lake at each station in triplicate on brackets attached to a PVC pipe that was attached to a post driven into the lake sediment. The spheres were allowed to dissolve in the lake over a 2-hr period and then dried for at least 48 hr at 40 °C to determine loss of gypsum mass ($g \, h^{-1}$).

The rate of gypsum dissolution was experimentally calibrated with respect to τ using the PES. Gypsum spheres were subjected to different shear stresses over a 2-hr period in the PES to determine relationships between the rate of dissolution and τ. Dissolution rates versus τ were determined at 10, 20, and 30 °C. These relationships were used to convert rates of gypsum dissolution, measured in the field in different plant beds at different temperatures, to τ (Figure 2).

Macrophyte biomass ($g \, m^{-2}$) in the vicinity of the *Chara* and *M. sibiricum* stations was determined in late August 1998, and in June 2000 using a 0.25-m^2 or 0.56-m^2 quadrat enclosure (according to the methods of Filbin and Barko (1985)). Macrophytes within the quadrat were removed using a rake and net. Some roots were inevitably included in each sample. Five to ten randomly selected samples were collected within a 20 x 20-m grid near each station. Samples were dried to a constant weight at 70 °C for standing crop determination. Ten randomly selected stems from each macrophyte bed were measured to the nearest millimeter.
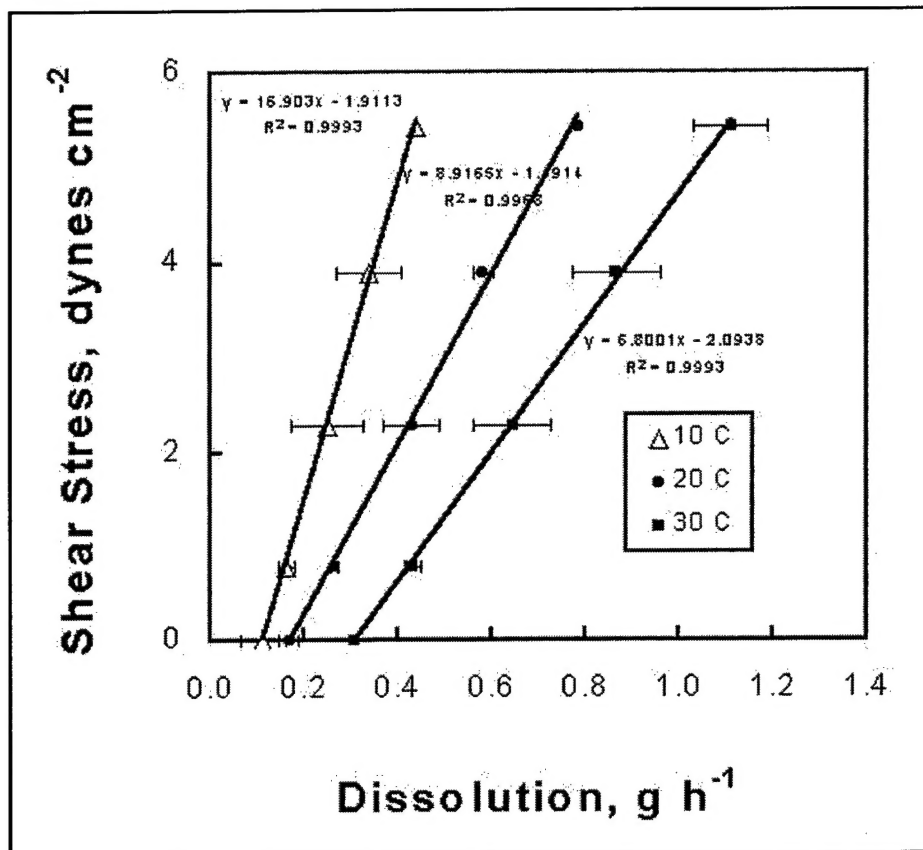
Figure 2. Relationship between gypsum sphere dissolution at 10, 20, and 30 °C and shear stress generated experimentally in the laboratory using a particle entrainment simulator

RESULTS: Sediments at the adjacent *M. sibiricum* and *Chara* sites exhibited a very high moisture content (85.2 percent ± 4.6 standard deviation; S.D.), high organic matter content (16.1 percent ± 2.2 S.D.), and low sediment density (0.20 g/mL ± 0.06 S.D.), indicative of fine-grained, flocculent sediments (Håkanson 1977). In the laboratory, resuspension of these sediments occurred at low levels of τ applied by the PES. TSS concentrations in the overlying water of sediment systems increased markedly as a function of increasing τ above ~1.2 to 1.4 dynes cm^{-2} (Figure 3). From these patterns, a τ_c of 1.4 dynes cm^{-2} was estimated for sediments located at the *Chara* and *M. sibiricum* stations in Lake Christina (Figure 3).

During late August 1998, macrophyte standing crop was 525 g m^{-2} (± 73 S.D.) at the *M. sibiricum* station and 245 g m^{-2} (± 45 S.D.) at the *Chara* station. *M. sibiricum* stems (~0.95 m in length) were within 0.25 m of the surface of the lake in late August and had formed a surface canopy (>1.2 m in length) by early September. *Chara* stems were only ~ 0.3-0.4 m in length and, thus, occupied only the near-bottom stratum of the lake during this period.

Wind speeds exceeded 30 km hr^{-1} on 18, 22, and 23 August and 1, 9, 10, and 13 September 1998 (Figures 4 and 5). Calculated bottom τ, estimated as a function of wind velocity, effective fetch, and wind direction, exceeded τ_c, determined experimentally in the laboratory using intact sediment cores
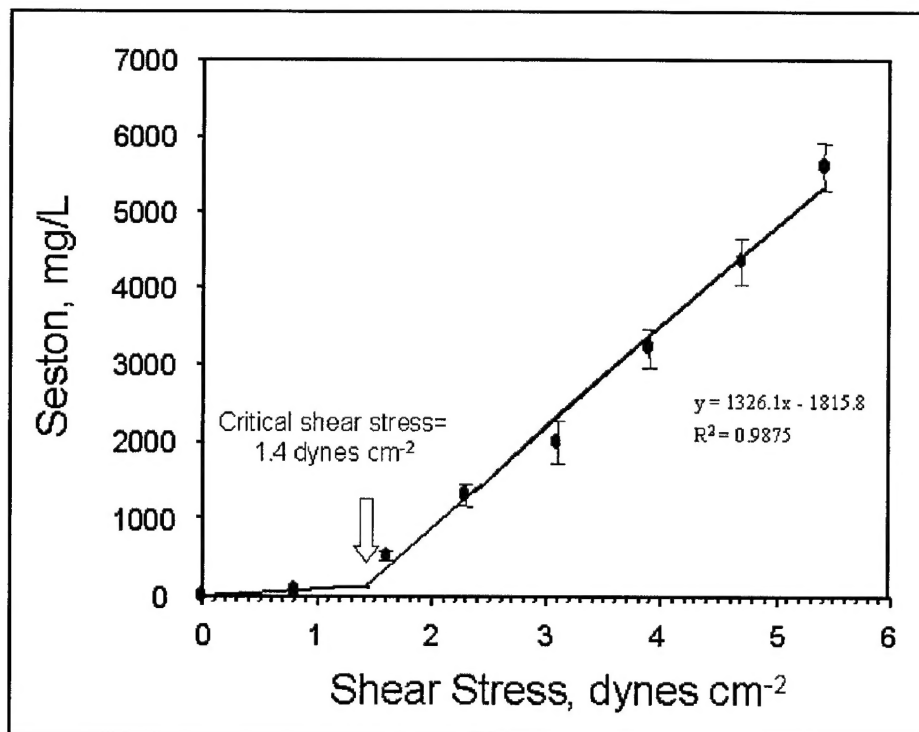
Figure 3. Variations in mean (± 1 S.E.; n=10) suspended seston concentration as a function of shear stress for intact sediment cores collected in the vicinity of the *Chara* and *Myriophyllum sibiricum* beds in Lake Christina. Shear stress was generated experimentally in the laboratory using a PES

and the PES, 16 percent of the time during the study period in 1998 (Figure 6). Thus, in the absence of submersed macrophytes, resuspension could have potentially occurred during these occasions when calculated bottom τ exceeded τ_c, resulting in peaks in turbidity in the water column.

During most of the study period, however, turbidity near the sediment interface was well under 50 NTU and nearly constant at both stations (Figures 4 and 5). In particular, turbidity values did not increase during very high sustained winds that occurred on 18, 22, and 23 August and 1, 9, 10, and 13 September 1998, suggesting that both the *Chara* and *M. sibiricum* communities were effectively inhibiting sediment resuspension during periods of high wind velocity.

An example of shear stress dynamics measured in *M. sibiricum* and *Chara* beds via gypsum sphere dissolution is shown in Figure 7 for the afternoon of 26 August 1998. On that date, winds blew steadily out of the SSW (195 deg) at nearly 30 km h^{-1} between approximately 1345 and 1700 hr (Figure 4). The effective fetch for both stations was nearly 1.8 km and calculated bottom τ ranged between 1.5 and 2.4 dynes cm^{-2}, which was greater than the τ_c estimated for sediments in the laboratory (i.e., 1.4 dynes cm^{-2}). These patterns indicated the strong potential for sediment resuspension in the absence of submersed macrophytes.

Within the *Chara* bed, apparent measured τ (i.e., determined from gypsum dissolution; $\tau_{apparent}$) was high near the lake surface as a result of wave activity (Figure 7). In contrast, $\tau_{apparent}$ was much less near the lake surface within the *M. sibiricum* bed, coincident with the occurrence of plant stems just
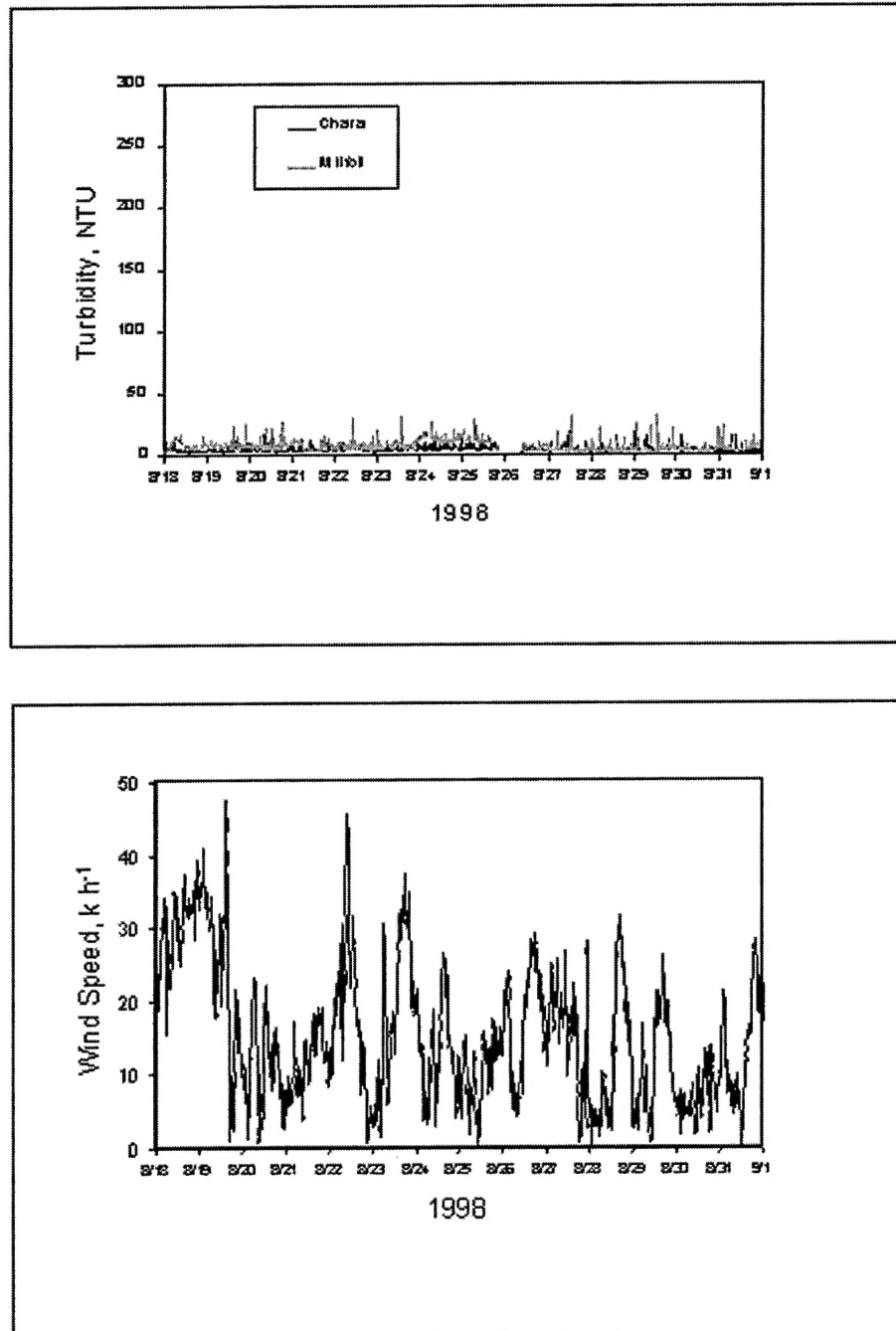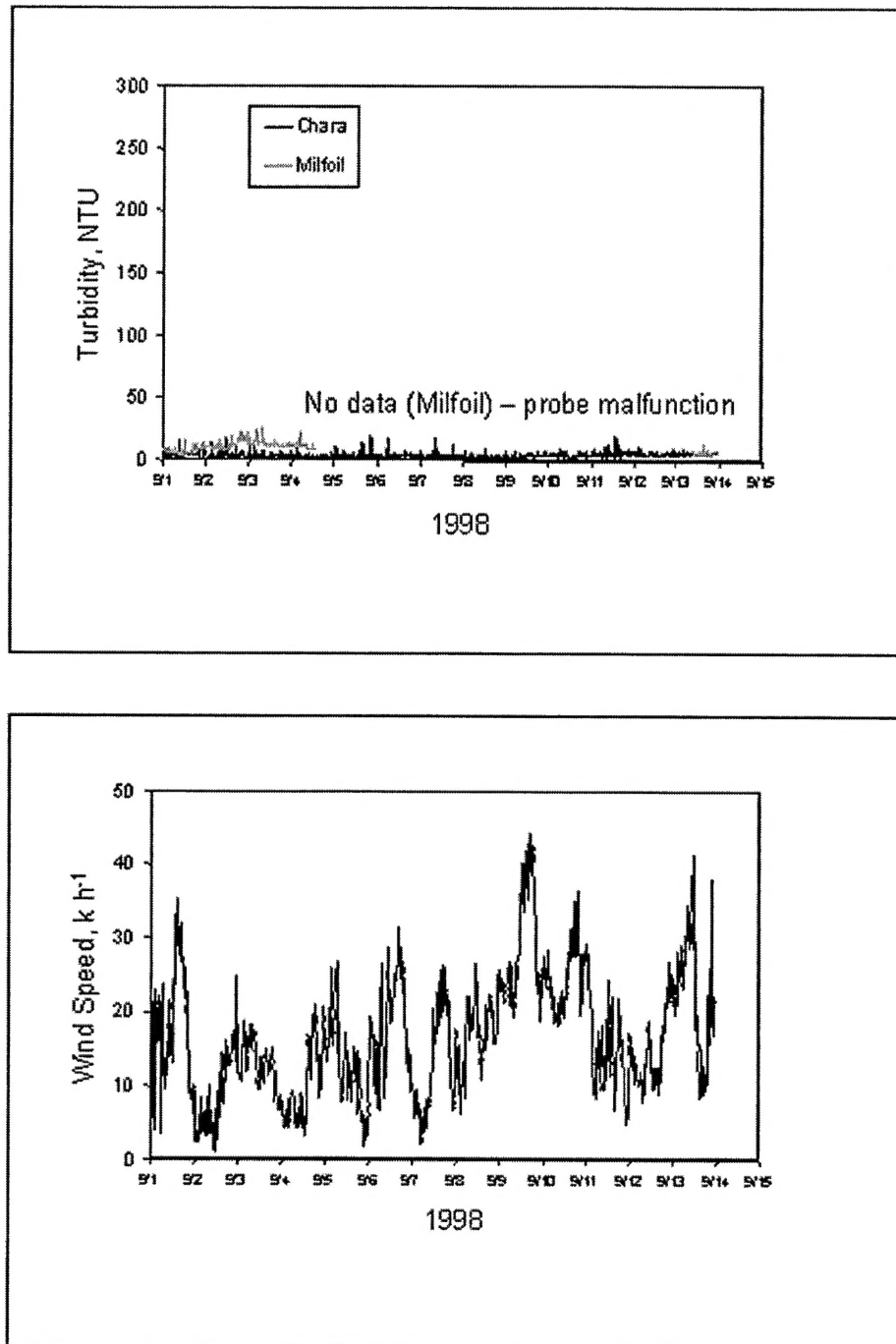
Figure 4. Seasonal variations in (upper) turbidity in the *Chara* and *Myriophyllum sibiricum* beds and (lower) wind speed in Lake Christina in late August 1998

below the lake surface (Figure 7). High *M. sibiricum* biomass and canopy-forming architecture resulted in dissipation of $\tau_{apparent}$ to zero in the lower 0.7 m of the water column of this macrophyte bed. Within the *Chara* bed, $\tau_{apparent}$ declined with increasing depth as well, but was nearly 1 dyne cm^{-2} at the 0.5-m depth. Within the zone of *Chara* growth near the sediment interface, however, it

Figure 5. Seasonal variations in (upper) turbidity in the *Chara* and *Myriophyllum sibiricum* beds and (lower) wind speed in Lake Christina in early September 1998

declined to zero. Turbidity near the sediment interface within both macrophyte beds was less than 10 NTU during the wind event of 26 August, and did not fluctuate, indicating that sediment resuspension was minimal in both beds on this date (Figure 4).
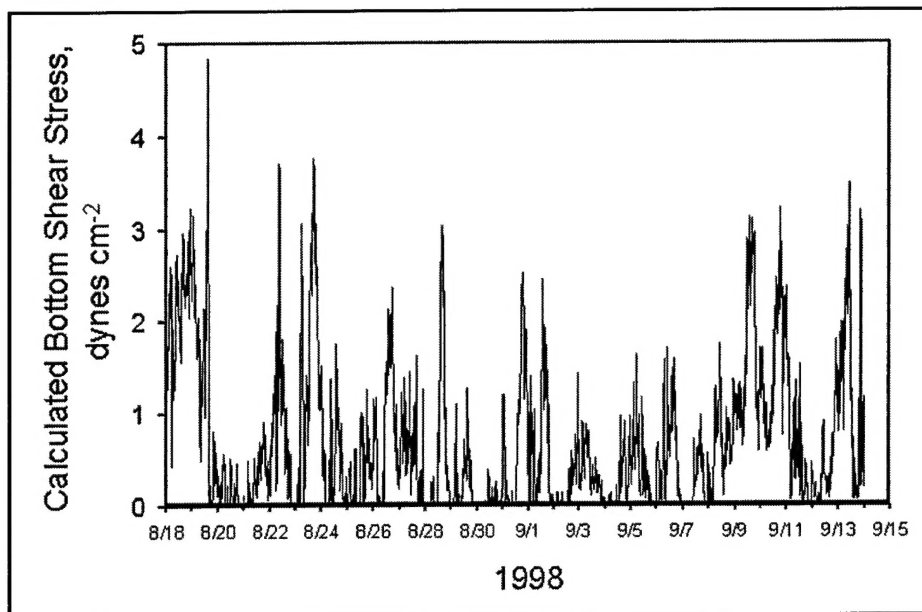
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Figure 6. Seasonal variations in calculated bottom shear stress (see methods) in late August through early September 1998. Calculated shear stress does not account for impacts that macrophytes have on wave activity
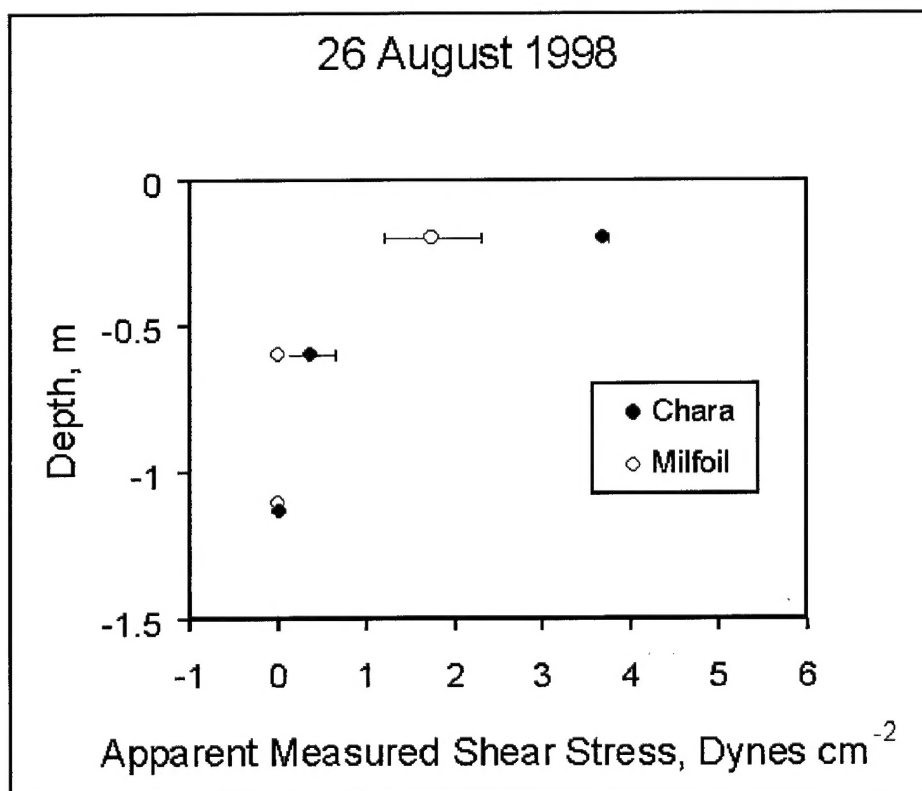

Figure 7. Depth-related variations in mean (n=3) apparent measured shear stress, measured as gypsum sphere dissolution, within the *Chara* and *Myriophyllum sibiricum* beds during the afternoon (i.e., 1430 to 1650 hours) on 26 August 1998. Horizontal black lines represent 1 standard error

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On 9 September, *M. sibiricum* stems had reached the surface of the lake. Winds blowing out of the south (180 deg) fluctuated between 35 and 45 km/h between 1100 and 1700 hr (Figure 5). The effective fetch for both stations during this period was ~ 1.5 km, resulting in a calculated bottom τ ranging between 2.1 and 3.1 dynes cm^{-2}, which was well above the τ_c of 1.4 dynes cm^{-2} for sediments in the lake.

As on 26 August, the $\tau_{apparent}$ within the *Chara* bed was greatest at the lake surface during the late morning and early afternoon of 9 September, due to wind-generated wave activity (Figure 8). At the 0.5-m depth in this macrophyte bed, it dissipated markedly to approximately 1 dyne cm^{-2}. Within the zone of *Chara* growth in the lower stratum of the water column, $\tau_{apparent}$ was approximately 0.6 dynes cm^{-2}, which was well below τ_c. In contrast, it was near zero throughout the water column within the *M. sibiricum* bed on 9 September (Figure 8).
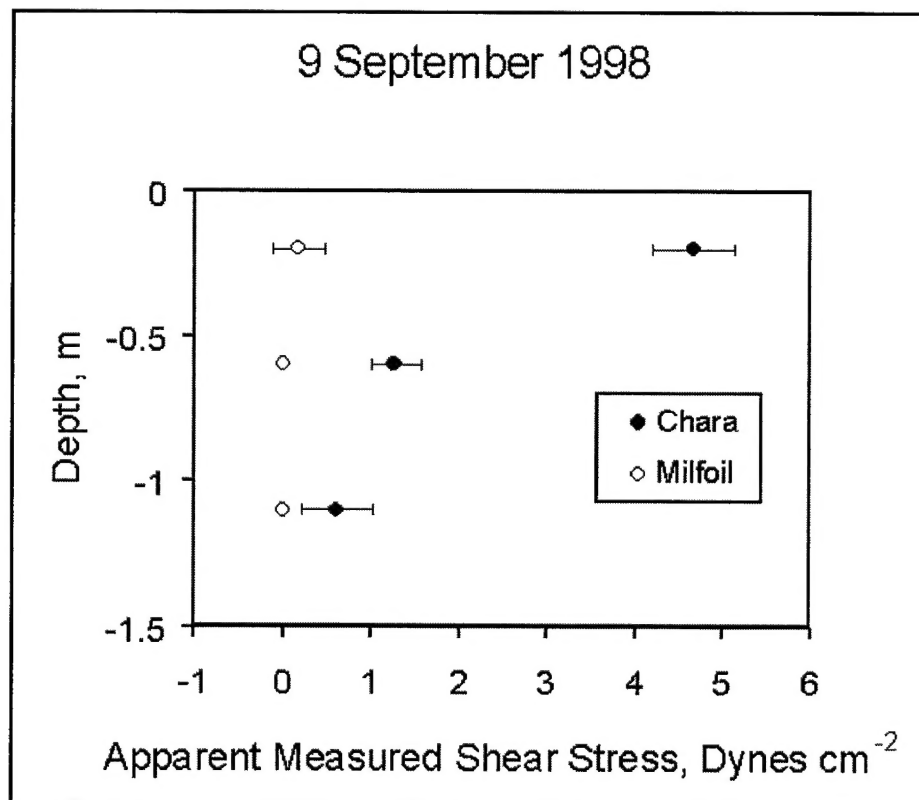

Figure 8. Depth-related variations in mean (n=3) apparent measured shear stress, measured as gypsum sphere dissolution, within the *Chara* and *Myriophyllum sibiricum* beds during the morning (i.e., 1145 to 1345 hr) on 9 September 1998. Horizontal black lines represent 1 standard error

During late June 2000, macrophyte biomass at these stations was much lower compared to levels observed in late August 1998. Mean biomass was only 11.6 g m^{-2} ($\pm$ 15.9 S.D.) in the *M. sibiricum* bed and 9.1 g m^{-2} ($\pm$ 15.9 S.D.) in the *Chara* bed. *M. sibiricum* stem length was approximately 62 cm, while *Chara* stem length was approximately 30 cm.

Strong winds (exceeding 30-40 km/hr) occurred on 19-21, 26, and 28 June 2000 (Figure 9). Calculated bottom τ exceeded τ_c (Figure 10) and turbidity exhibited peaks on these dates (Figure 9) in both the *M. sibiricum* and *Chara* beds. These patterns contrasted markedly with turbidity patterns observed in 1998, when the macrophyte standing crop was an order of magnitude higher.
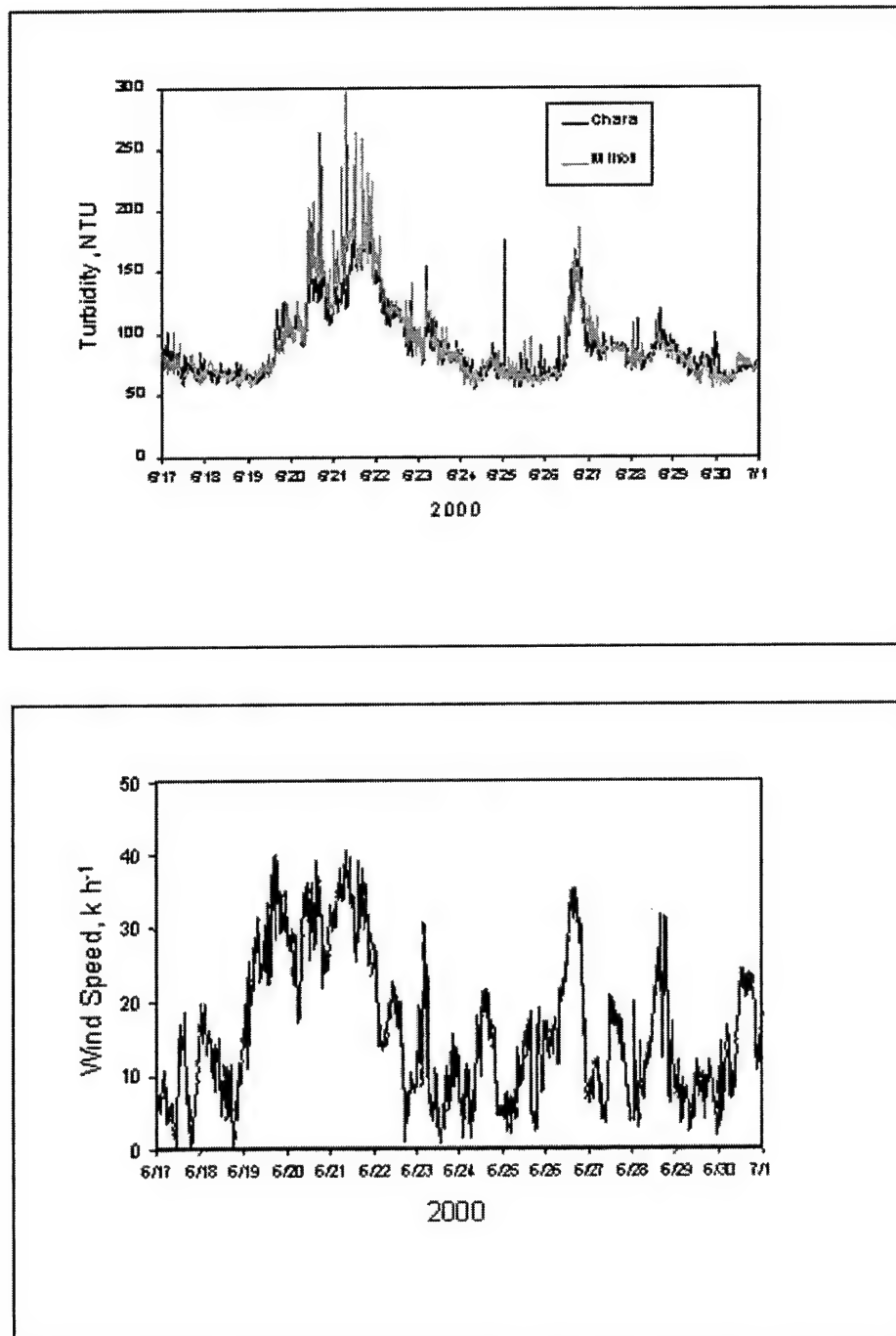
Figure 9. Seasonal variations in (upper) turbidity in the *Chara* and *Myriophyllum sibiricum* beds and (lower) wind speed in Lake Christina in June 2000
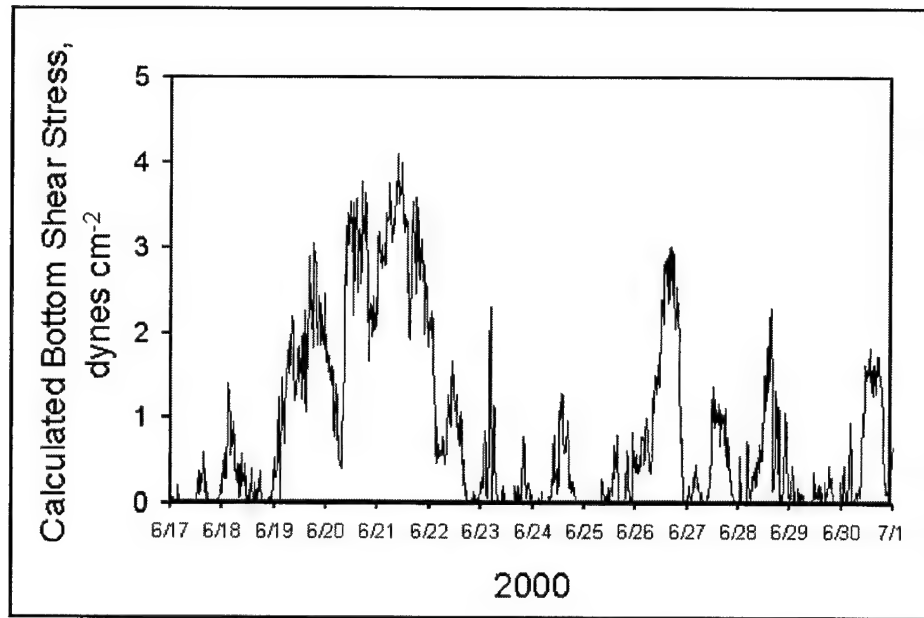
Figure 10. Seasonal variations in calculated bottom shear stress (see methods) in June 2000. Calculated shear stress does not account for impacts that macrophytes have on wave activity

An example of shear stress dynamics during a period of low macrophyte biomass is shown in Figure 11 for the afternoon of 21 June 2000. On that date, winds blew out of the southwest at 29 to 34 km hr^{-1} and the effective fetch was approximately 3.1 km. Gypsum dissolution was very high near the lake surface and dissipated as a function of depth at both the *M. sibiricum* and *Chara* stations (Figure 11). Near the sediment surface, the $\tau_{apparent}$ was approximately 2.0 dynes cm^{-2} at both stations, which exceeded τ_c for the sediments. Coincident with $\tau_{apparent} > \tau_c$ was the occurrence of peaks in turbidity in the water column (Figure 9), indicating the occurrence of sediment resuspension.

One important observation from the results of gypsum dissolution in June of 2000 is that the $\tau_{apparent}$ (2.0 dynes cm^{-2}) near the sediment interface was less than the calculated bottom τ of 3.1 dynes cm^{-2}. One explanation for this discrepancy in $\tau_{apparent}$ versus calculated bottom τ is that the PES-calibrated gypsum spheres underestimated bottom shear stress calculated from wave theory. However, if one assumes that the gypsum spheres accurately measured τ, the results suggest that even at very low biomass levels, both the *M. sibiricum* and *Chara* beds had an impact on bottom τ in the lake in June. Thus, although sediment resuspension did occur during wind events in June, low plant biomass may have been effective in reducing the bottom τ to a level that was lower than that predicted using wave theory. Overall, relative to a 1:1 relationship between $\tau_{apparent}$ and calculated bottom τ, $\tau_{apparent}$ was approximately half that of calculated bottom τ at low biomass levels for both macrophyte species (i.e., < 20 g/m^2 biomass; Figure 12). At high biomass levels (i.e., > 200 g/m^2), $\tau_{apparent}$ was nearly zero at all levels of calculated bottom τ.

DISCUSSION: Even at high wind speeds (i.e., > 30 km h^{-1}), $\tau_{apparent}$ near the sediment interface was nearly zero, and sediment resuspension was nonexistent, in both the *M. sibiricum* and *Chara* beds in 1998 when biomass levels were high (>200 g m^{-2}). At these high biomass levels, the
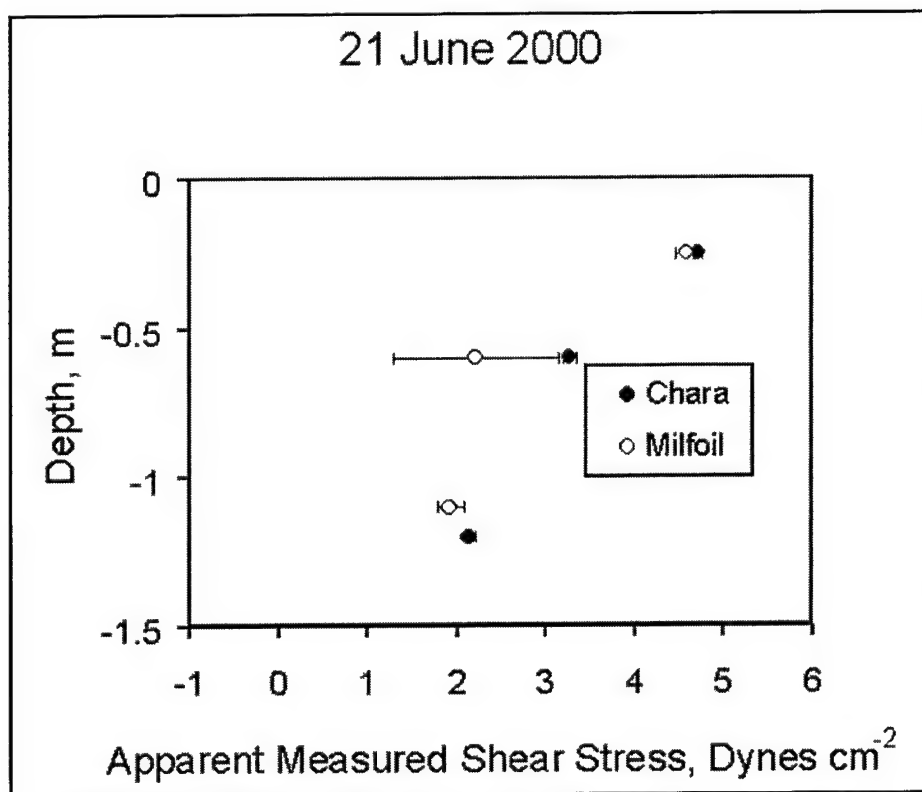
Figure 11. Depth-related variations in mean (n=3) apparent measured shear stress, measured as gypsum sphere dissolution, within the *Chara* and *Myriophyllum sibiricum* beds during the late morning-early afternoon (i.e., 1145 to 1345 hoiurs) on 21 June 2000. Horizontal black lines represent 1 standard error

canopy-forming *M. sibiricum* bed reduced $\tau_{apparent}$ throughout the water column whereas the meadow-forming *Chara* bed most effectively reduced $\tau_{apparent}$ primarily in the lower water column, due primarily to differences in plant architecture. These results are important to lake managers in demonstrating that meadow-forming macrophyte species such as *Chara* or *Vallisneria* may provide sediment stability while allowing open surface water conditions for boating and other recreational activities. Similarly, Van den Berg et al. (1998) found that dense meadow-forming *Chara* beds were very effective in reducing sediment resuspension and turbidity in Lake Veluwemeer, The Netherlands.

It is not known why biomass levels declined at the sampling locations, and lakewide, between the summers of 1998 and 2000. However, during June of 2000 biomass was an order of magnitude lower in both plant beds compared to biomass levels observed in late August 1998. Unlike patterns observed in 1998, periods of sediment resuspension were associated with high winds in both plant beds in June 2000. However, it appeared that even at very low biomass levels, both *M. sibiricum* and *Chara* reduced $\tau_{apparent}$ near the sediment interface, relative to calculated bottom τ. Thus, by reducing τ at the sediment interface at these low biomass levels, higher wind speeds would be required to achieve resuspension (i.e., an increase in the critical wind threshold required to resuspend sediment; Carper and Bachmann (1986)). Nevertheless, the τ_c of the sediment was
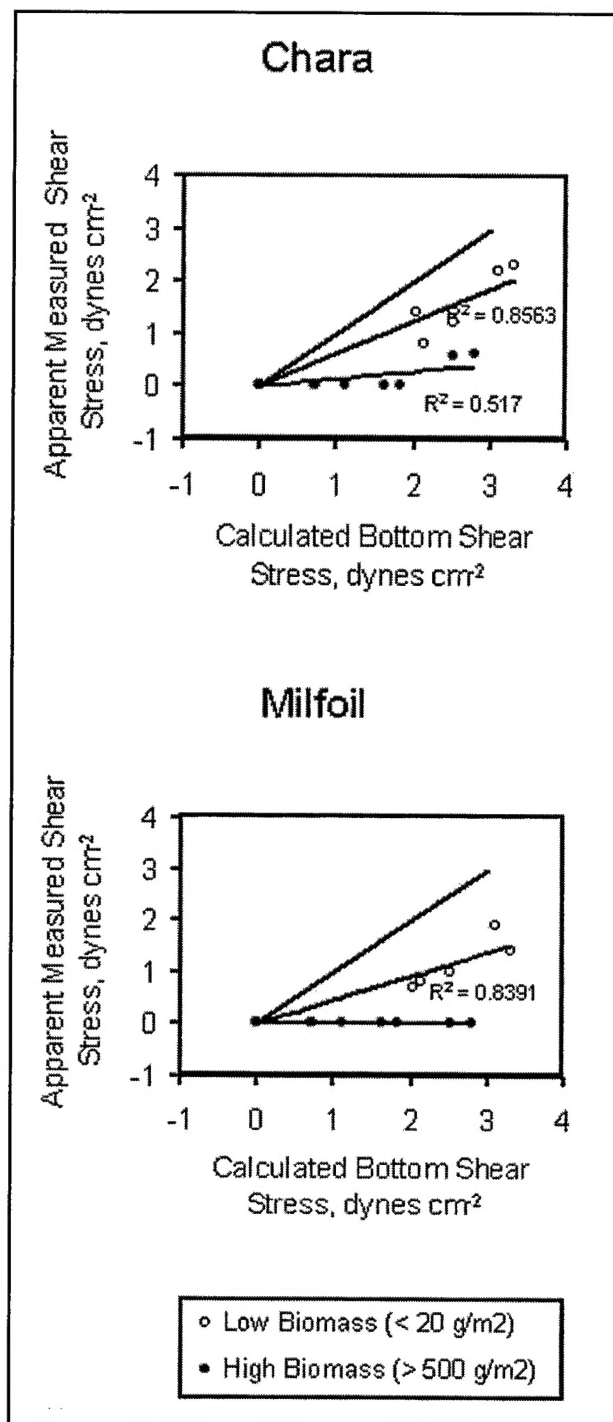
Figure 12. Calculated bottom shear stress (wave equations; see methods) versus apparent measured shear stress (gypsum sphere dissolution) for low and high biomass levels at the *Chara* and *Myriophyllum sibiricum* stations in Lake Christina. The 1:1 line is shown for comparison

exceeded in June 2000, due to greatly reduced macrophyte coverage, resulting in sediment resuspension.

The results of this study have implications for the management of aquatic macrophytes and water quality in shallow systems. Information obtained from these two general biomass levels and architectural types (i.e., canopy versus meadow) may be used to modify resuspension models (i.e., Bailey and Hamilton (1997), Hamilton and Mitchell (1996)) to account for the impacts of macrophyte communities on bottom τ and sediment resuspension. For instance, the calculated bottom τ could be reduced as a function of anticipated macrophyte biomass level. In particular, these models, with adjustments made to bottom τ to account for macrophyte biomass, could be used to explore optimal locations for establishment of macrophyte beds to reduce sediment resuspension in shallow systems.

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